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Research Paper

Research on membrane absorption air-conditioning system with more than one stage

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HIGHLIGHTS

- The actual COP of the single system approaches 3.
- Theoretical and experimental research has been made for the double-stage system.
- The influences of different factors have been exposed for the double-stage system.
- Multi-stage membrane system has been analyzed.

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ABSTRACT

To overcome the worldwide energy poverty and climate change, greener buildings are urgently needed. The air-conditioning system, as a huge energy consumer in buildings, must be more energy conservative and environment friendly. Absorption air-conditioning system is an idea option except for its low performance caused by energy waste in the thermal regeneration process. That can be improved with the membrane regeneration method driven by electric power. However, the performance is unstable with higher concentration difference. Double-stage membrane system can solve this problem by reducing the concentration difference, but yet lacks experiment support. To improve, theoretical and experimental work has been made: Experiments have been conducted to test the true performance. Based on which, analysis has been made on some influential parameters. It has revealed the influences of the solute concentration, voltages, temperatures and the transferred solute mass. The double-stage system has better performance as the energy efficiency increases with the decreasing concentration difference. Under some conditions, the performance of the double-stage system is 20% higher than that of the single-stage system. When the absorbent solution is LiBr, the maximum coefficient of performance of the double-stage system can be higher than 3. That makes it a promising system for future application.

1. Introduction

The uncontrolled use of nature resources and energy reserves has led to environmental damages. The building sector consumes more than 30% of the total energy consumption, while the air-conditioning system is a leading energy consumer in buildings [1–3]. The widely used vapor compression system heavily depends on the electric power and the refrigerant brings environmental problems. To improve, many innovations have been developed, such as adsorption technique, jet refrigeration and magnetic refrigeration: Angrisani et al. [4] analyzed a plant equipped with a silica-gel desiccant wheel. Through dynamic simulations, a maximum primary energy saving is more than 10%. Li et al. [5] researched a solar driven two-wheel two-stage desiccant cooling/heating system, the system can achieve an average thermal *COP* of about 0.97 in hot and humid climate. Thongtip et al. [6] discussed the performance of R141b jet-pump refrigerator based on an alternative analysis. Monfared [7] established the model of magneto-caloric refrigeration systems with two approaches and the *COP* was simulated. Absorption air-conditioning system is another promising replacement as it favors renewable energy, such as solar energy [8], geothermal energy [9] and wind energy [10], and the refrigerant is less harmful or even completely environment-friendly [11,12]. However, the low performance of conventional absorption system has restricted its development. On the purpose of performance improvement, many progresses have been made: Avanessian et al. [13] compared different water-cooled $LiBr–H_2O$ absorption systems from the aspects of energy,

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Nomenclature

c	mass concentration of solute, %
COP	coefficient of performance
ED	electrodialysis
AM	anion-exchange membrane
CM	cation-exchange membrane
$LDCS$	liquid desiccant cooling system
F	Faraday constant, s·A/mol
l_w	latent heat of evaporation of water, kJ/kg
M_s	molecular weight of the solute in the absorbent solution, g/mol
N	cell number
U	voltage, V
z	electrochemical valence
P	power, kW
Q	acquired cooling capacity, kW
m	mass flow rate, kg/s
i	current density, A/m^2

Greek letters

ζ	current efficiency
Δ	thickness of a unit cell, m
γ	area resistance of ion-exchange membrane, Ω·m^2
ρ	density of the solution, kg/m^3
Λ	equivalent conductivity, S/m

Superscripts

c	concentrated cell in double-stage system
d	diluted cell in double-stage system

Subscripts

1	entrance of regenerator of double-stage system
2	exit of regenerator of double-stage system
s	solute
w	water
v	volume
i	in
o	out
c	concentrated cell in single-stage system
d	diluted cell in single-stage system
$single$	Single-stage system
$double$	double-stage system
ab	absorber
mol	mole
Reg 1, Reg 2	regenerator 1, regenerator 2

exergy and economy. In those works, single-effect system is uneconomical, in certain cases, the total exergy efficiency of the system including direct-fire double-effect chiller are about 80% higher than the systems including hot-water double-effect and single-effect chillers. Li et al. [14] investigated the solar air-cooled double-effect LiBr-H_2O absorption cooling system in subtropical city. The *COP* varied in a range 1.1–1.3 according to the data for several months. Talukdar et al. [15] proposed a combined vapor power cycle and double-effect LiBr-H_2O absorption refrigeration system. Under certain parameters, the *COP* is increased to 1.4. Compression-absorption refrigeration system also attracts a lot of attentions. A hybrid system proposed by Bouaziz et al. [16] is combined with two conventional absorption stages (two absorbers, two generators, condenser and evaporator) and a compressor. The *COP* of the hybrid cycle is nearly 25–32% greater than that for the classical cycle. Jain et al. [17] developed a thermodynamic model for cascaded vapor compression-absorption system which consists of a vapor compression refrigeration system coupled with single effect vapor absorption refrigeration system. According to their works, the electric power consumption is reduced by 61% compared with a conventional compression refrigeration system.

Recently, membrane technologies are emerging as another choice to improve the efficiency of absorption system: Wang et al. [18] presented a absorption refrigeration system with vacuum membrane distillation. Duong, Ma et al. [19,20] demonstrated the viability of membrane distillation for absorbent solution regeneration. Al-Jubainawi et al. [21] investigated the mass transfer mechanisms and the performance of membrane electrodialysis (ED) for regenerating LiCl solution commonly used in liquid desiccant cooling system (LDCS). Among them, the application of ion exchange membrane shows great potential in bettering the regeneration performance [20,21]. The low efficiency of the conventional absorption system mainly lies in the energy waste (in the form of extra heat) of the thermal regeneration process. Membrane ED regeneration method is a technique based on the transport of ions through ion exchange membranes under the influence of an electrical field [22–24]. So it can avoid the extra heat and concentrate salt solution more efficiently [20,25,26]. Cation-exchange and anion-exchange membranes (CM and AM) are placed alternately between the cathode and the anode. When a potential difference is applied between electrodes, the cations go through CM, and are retained by AM, the anions go through AM, and are retained by CM. This movement causes a rise in the ions concentration in some compartments (concentrated cells) and decrease in the adjacent ones (diluted cells). By this means, both concentrated absorbent solution and pure water can be obtained.

Based on ED methods, single-stage membrane regeneration method is proposed for absorption refrigeration system and LDCS [20,21,25,26]. Driven by solar photovoltaic power, an ED stack is used as a regenerator, which saves the condenser. This method has been proved to be applicable for absorption refrigeration system, and the *COP* can be even as high as vapor compression system under some conditions [18,25]. However, the performance could be unstable when there is a big concentration difference across the membranes. It leads to an increasing mass transfer according to the concentration gradient, in the opposite direction of the regeneration process [22]. We proposed a double-stage regeneration method for LDCS as a possible solution: two regenerators make regeneration divided into two steps, which lows the concentration difference between two adjacent cells [26]. Nevertheless, it is a preliminary simple analysis without experiment data support. For one thing, it only concentrates on the energy consumption of LDCS but doesn't go further considering the whole performance. For another thing, the concentration difference is taken as the only influencing facto, but there are actually more related factors, like the voltage ratio between different stages. The impacts of those factors are complicated and needs more discussion. Moreover, there's no experimental work to support the idea of the double stage system and expose the influence of the parameters in detail. The analysis has not been conducted thinking about the practical working conditions, making it hard to guide the real system configuration, in no saying of the performance optimization. Therefore, to fully explore the idea of double-stage system, further research has been made in this paper: Experiments have been conducted to reveal the influence of the concentration difference across the membranes. The results show the regeneration efficiency drops rapidly with rising concentration difference, which supports the idea of double-stage system. The model of the whole performance has been established for the absorption air-conditioning system. Based on the model, analysis has been made to reveal the influences of some important factors on the system *COP*. Furthermore, the practical performance has been predicted

with the experimental data. Since the double-stage system is more efficient than the single-stage system by reducing the harmful concentration difference in mass transfer, will it be better with more stages? To answer this question, this paper has also discussed the multi-stage system.

2. Materials and methods

2.1. Single-stage membrane regeneration system

2.1.1. System description

Single-stage system is described in Fig. 1. The regenerator is basically an ED stack. In alternating cells absorbent solution is concentrated and diluted, respectively. The adjacent cells are referred to as a cell pair (shown in Fig. 2). The red and pink lines depict the regeneration cycle. At the beginning, the weak absorbent solution stream from the absorber is concentrated in all the concentrate cells, then the effluent is back to absorber and continues to absorb the water vapor from evaporator, the heat release will be taken away by the heat rejection device. Excess strong solution will be made in the regeneration round and accumulate in Solution Storage Tank 1 [25]. The blue and dark blue lines depict the dilution cycle. All the diluted cells are feeding with the absorbent solution stream from Solution Storage Tank 2, which will be recycled from the diluted cells to Solution Storage Tank 2 until it has finally become purified water. Then, the purified water in Tank 2 will be stored in Water Storage Pool (green lines) as the refrigerant provided to evaporator, and Solution Storage Tank 1 and 2 will exchange the role they played before. The cycle time of regeneration is comprehensively determined by the flow rate and the mass transfer rate between diluted and concentrated cells, which can be designed in specific conditions. Moreover, the water produced during the cycle time must be equal to the amount of water required for the refrigeration cycle. Like this, Tanks 1 and 2 keep on alternating their roles and both the strong absorbent solution and the purified water are acquired.

Both driven by electric power, the membrane regeneration method makes the COP of the absorption system as competitive as the vapor compression system [26,27]. For the comparison between the traditional thermal regeneration method and membrane regeneration method, it should be discussed in different situations. Situation 1 assumes the thermal and membrane methods are both driven by electric

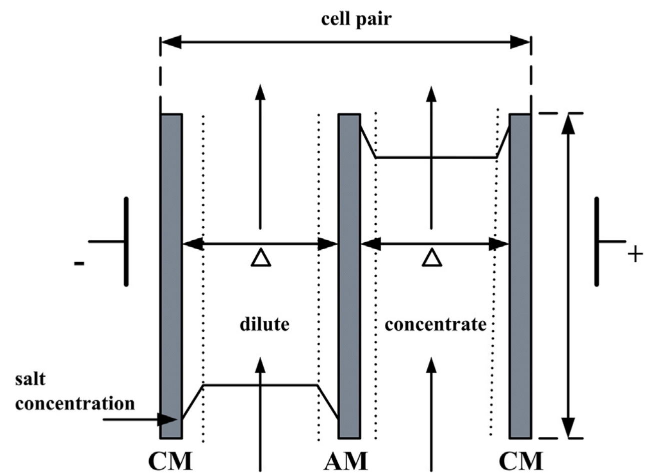


Fig. 2. Configuration of an ED cell pair.

power. The heat power for the thermal method is from a pure resistance circuit, which completely converts the electric power into thermal energy. In this situation, the membrane regeneration method has better performance. Situation 2 assumes both the thermal and membrane methods are driven by solar energy. The thermal method is driven by solar energy converted into heat while the membrane method is driven by solar energy converted into electricity. In this situation, the thermal method has better performance as the efficiency of solar-heat conversion is 2 times higher than that of solar-electricity (PV) conversion [26–29]. Generally, if we consider the absorption system as an alternative of the vapor compression system, the development of the membrane regeneration method will be a better option.

2.1.2. Performance

The power of single-stage system is given by [25]:

$$P_{\text{single}} = UI = \frac{zFU\dot{m}_s}{M_s \zeta N} \tag{1}$$

P_{single} is the power of single-stage regenerator, the unit is kW; U is the applied voltage, the unit is V; I is the total electric current passing

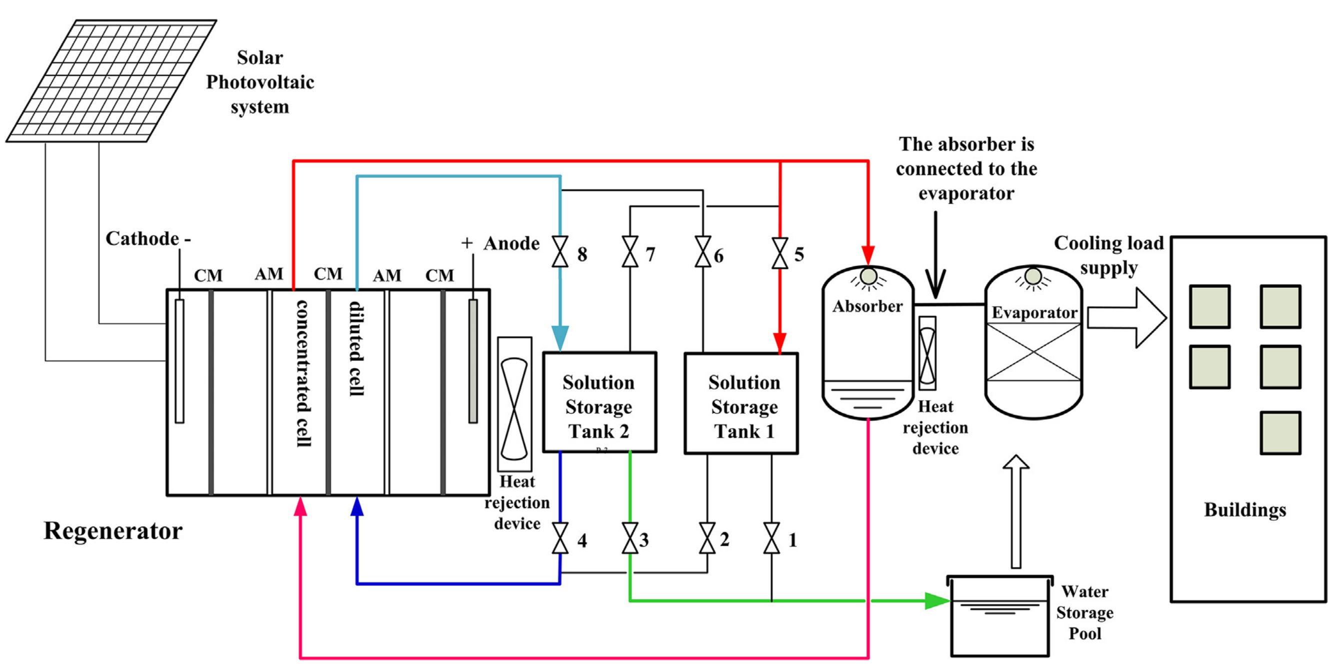


Fig. 1. Single-stage membrane regeneration system.

through the stack, the unit is A; ζ is the current utilization efficiency; z is the valence; and F is the Faraday constant, the unit is s·A/mol; N is the number of cell pairs; $\dot{m}_s$ is the total mass of the solute transferred per second from the diluted cells to the concentrate cells, the unit is kg/s; M_s is the molecular weight of the solute in the absorbent solution, the unit is g/mol.

The *COP* of single-stage system is given by [25]:

$$COP_{\text{single}} = \frac{Q}{P_{single}} = \frac{l_w M_s N\zeta(1-c_{o,c})}{zFUc_{o,c}} \tag{2}$$

Q is the acquired cooling capacity, the unit is kW, $c_{o,c}$ is the mass concentration at the exit of concentrated cells of the regenerator, the unit is %. The mass relationship is shown as Fig. 3.

2.2. Relationship between performance and concentration difference

Single-stage membrane regeneration is an efficient way to improve the performance of absorption air-conditioning system [27–29]. However, research also found the performance of the single-stage system is lower with enlarging concentration difference between the adjacent cells. The reason for that is the mass transfer according to the concentration gradient, which is in the opposite direction of the regeneration process. Thus it reduces the regeneration effect and causes lower performance. Experiment has been designed as Fig. 4 and conducted to investigate this phenomenon. Current efficiency is used to present the influence of the concentration difference on the performance. Its definition is [25]:

$$\zeta = \frac{zFm_{c,v}(c_{o,c,mol}-c_{i,c,mol})}{NI} \tag{3}$$

$c_{i,c,mol}$, $c_{o,c,mol}$ are respectively the mole concentration at the entrance and exit of the concentrated cells, the units are mol/L; $m_{c,v}$ is the volume flow rate of solution passing through the concentrated cells, the unit is L/s. Concentration difference between concentrated and diluted cells was adopted as logarithmic mean difference.

Take LiCl solution as the absorbent. In Fig. 4, the solution passed through the membrane regenerator. One stream cycled between the diluted cells and Solution Storage Tank 3. Another stream was first pumped from Solution Storage Tank 1 to the concentrated cells. After regeneration, it was sent to Solution Storage Tank 2, which was empty at the beginning. When Solution Storage Tank 2 was full of absorbent solution, it exchanged the role with Solution Storage Tank 1 and the cycle of the concentrate stream continued. Before and after regeneration, the solution concentration was measured with the concentration meters, the type was PXSJ-216 (Rex Co., Ltd) and the accuracy was ± 0.5%. The solution temperature was detected with Pt 100 RTDs with the accuracy of ± 0.1 °C. The flow rates of the two streams were recorded with flow rate meters, the accuracy of which was ± 1%. The processing time was 1 h. The configuration of the membrane regenerator is shown as Fig. 5. It adopted titanium alloy electrodes. The size of the regenerator was 350 mm × 200 mm × 123.5 mm. The thickness was 123.5 mm, which is the sum of the membrane pairs, division plates and compartments. The membrane type was CM for the cation exchange membrane and AM for the anion exchange membrane (Asahi Glass Co.). There were 25 membrane pairs and the size of every single membrane was 280 mm × 160 mm. The effect area was 0.021 m^2 under the electric field.

As introduced above, larger concentration difference between adjacent cells will negatively affect the system performance. The experiment results will validate this analysis and reveal the influence in detail, and thus supports the idea of adopting double-stage or multi-stage system for better performance.

2.3. Double-stage membrane regeneration method for absorption air-conditioning system

2.3.1. System description

Fig. 6 is the sketch of double-stage system. The red and pink lines depict regeneration cycle while the blue and dark blue depict dilution cycle. At the beginning, all the absorbent solution in diluted cells is sent from solution storage Tank 2; all the concentrated cells are feeding with the weak absorbent solution stream from the absorber. Solution from absorber is primarily concentrated in Regenerator 1, and then sent into Regenerator 2 for secondary concentration; solution from storage Tank 2 is primarily diluted in Regenerator 2, and then sent to Regenerator 1 for secondary dilution. In this way, the concentration of the diluted and concentrated cells are both high for Regenerator 2 and relatively lower for Regenerator 1, which makes the regeneration more stable. Then, strong absorbent solution out of Regenerator 2 will be sent into absorber, and other steps are same as single-stage system.

2.3.2. Performance

As for double-stage system, the power is the sum of the power of the two regenerators. According to Eq. (1), giving the power of double-stage system:

$$P_{double} = P_{Reg1} + P_{Reg2} = \frac{zF}{M_s}\left(\frac{U_1\dot{m}_{s1}}{N_1\zeta_1} + \frac{U_2\dot{m}_{s2}}{N_2\zeta_2}\right) \tag{4}$$

P_{double} is the sum power of the double-stage system, kW; P_{Reg1} and P_{Reg2} are respectively the power of Regenerator 1 and 2, the units are kW; U_1 and U_2 are respectively the voltages of Regenerator 1 and 2, the units are V; N_1 and N_2 are respectively the cell pairs of Regenerator 1 and 2; $\dot{m}_{s1}$ and $\dot{m}_{s2}$ are respectively the mass of the solute transferred per second from the diluted cells to the concentrated cells in Regenerator 1 and 2, the units are kg/s.

The diagram indicating the mass balance is depicted in Fig. 7. c_1^c, m_1^c, are the solute concentration and the solution mass flow rate at the entrance of the concentrated cells of Regenerator 1; c_3^c, m_3^c, are the solute concentration and the solution mass flow rate at the entrance of the concentrated cells of Regenerator 2; c_2^c, m_2^c, are the solute concentration and the solution mass flow rate at the exit of the concentrated cells of Regenerator 2; c_1^d, m_1^d, are the solute concentration and the solution mass flow rate at the entrance of the diluted cells of Regenerator 2; c_3^d, m_3^d, are the solute concentration and the solution mass flow rate at the entrance of the diluted cells of Regenerator 1; c_2^d, m_2^d, are the solute concentration and the solution mass flow rate at the exit of the diluted cells of Regenerator 1.

The acquired cooling capacity Q can be treated as the absorbed heat amount by evaporating $\dot{m}_w$ kg water per second:

$$Q = l_w\dot{m}_w \tag{5}$$

The *COP* is:

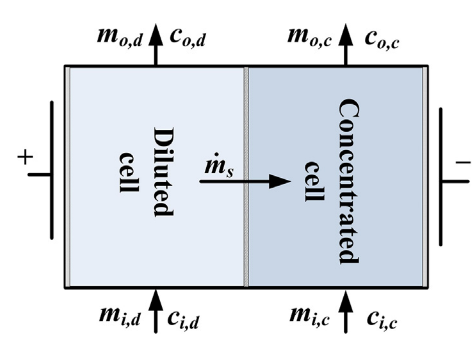


Fig. 3. Mass relationship of single-stage system.

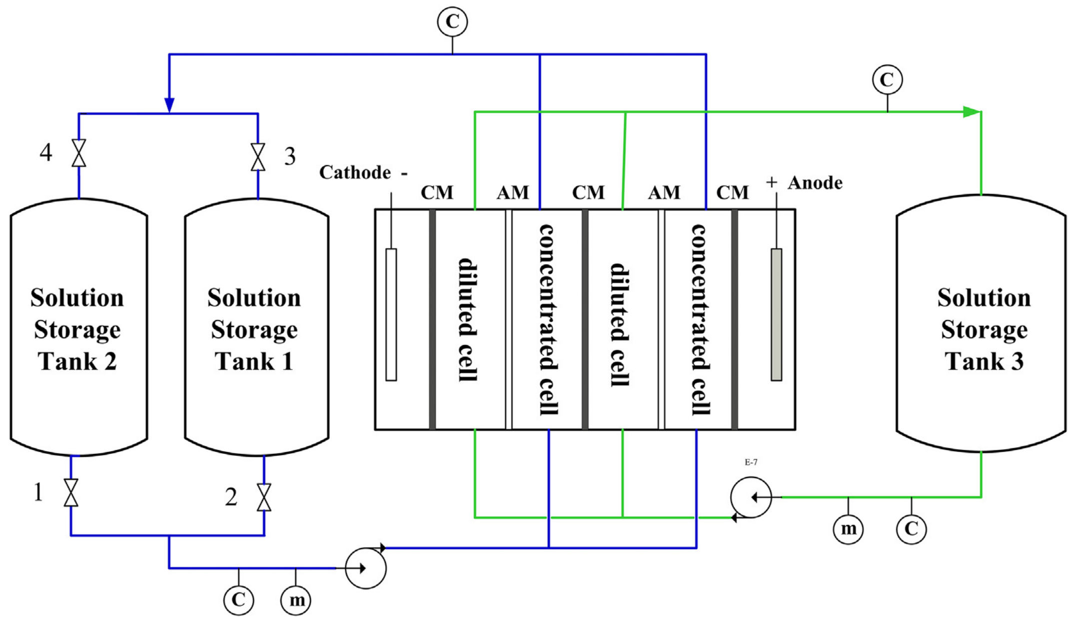


Fig. 4. Experimental system.

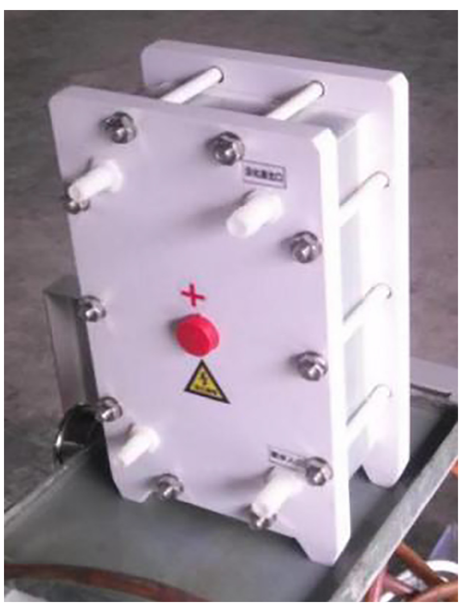


Fig. 5. ED regenerator.

$$COP_{double} = \frac{Q}{P_{double}} = \frac{l_w \dot{m}_w}{\frac{zFU_1\dot{m}_{s1}}{M_s\zeta_1N_1} + \frac{zFU_2\dot{m}_{s2}}{M_s\zeta_2N_2}} \quad (6)$$

There are the equations for mass balance of the solution in concentrated cells:

$$m_1^c + \dot{m}_{s1} = m_3^c \quad (7)$$

$$m_1^c c_1^c + \dot{m}_{s1} = m_3^c c_3^c \quad (8)$$

$$m_3^c + \dot{m}_{s2} = m_2^c \quad (9)$$

$$m_3^c c_3^c + \dot{m}_{s2} = m_2^c c_2^c \quad (10)$$

According to the equations above, and the total mass of the transferred solute per second is $\dot{m}_s$:

$$\dot{m}_s = \dot{m}_{s1} + \dot{m}_{s2} = (m_3^c - m_1^c) + (m_2^c - m_3^c) = m_2^c - m_1^c \quad (11)$$

$$\dot{m}_s = \dot{m}_{s1} + \dot{m}_{s2} = m_2^c c_2^c - m_1^c c_1^c \quad (12)$$

$$\dot{m}_s = \frac{c_2^c - c_1^c}{1 - c_1^c} m_2^c \quad (13)$$

The mass equation in the absorption-refrigeration process is show as:

$$m_{i,ab} + \dot{m}_w = m_{o,ab} \quad (14)$$

$$m_{i,ab} c_{i,ab} = m_{o,ab} c_{o,ab} \quad (15)$$

$m_{i,ab}$ stands for the mass flow rate of the solution at the entrance of the absorber and its concentration is $c_{i,ab}$; $m_{o,ab}$ stands for the mass flow rate of the solution at the exit of the absorber and its concentration is $c_{o,ab}$. In fact, $m_{o,ab} = m_1^c$, $c_{i,ab} = c_2^c$, and $c_{o,ab} = c_1^c$. Integrate Eqs. (14), (15):

$$\dot{m}_w = m_{o,ab} - \frac{m_{o,ab} c_{o,ab}}{c_{i,ab}} = m_1^c \left(1 - \frac{c_1^c}{c_2^c}\right) = \frac{(1 - c_2^c)(c_2^c - c_1^c)}{(1 - c_1^c) c_2^c} m_2^c \quad (16)$$

The solute mass transferred in Regenerator 1 is one part of the total solute mass transferred, there must be a proportional relationship between them, so we can assume $\dot{m}_{s1} = k_1 \dot{m}_s$, $\dot{m}_{s2} = (1 - k_1)\dot{m}_s$, if $\zeta_1 = \zeta_2 = \zeta$, $N_1 = N_2 = N$, according to Eqs. (6), (13), (16), the *COP* can be obtained:

$$COP_{double} = \frac{l_w M_s N\zeta (1 - c_2^c)}{zFU_1 c_2^c} \left(\frac{1}{k_1 + U_2/U_1(1 - k_1)}\right) \quad (17)$$

There are many electrical parameters in Eq. (17), they have a close relationship with the thermodynamic parameters, such as current efficiency ζ, it is closely related to the temperature of the regenerator: the higher the temperature, the lower current efficiency [27]. Distinct from single-stage system, mass transfer ratio k_1 and voltage ratio U_2/U_1 are additional as the equation shows. Actually, voltages applied on Regenerator 1 and 2 are defined as follows [26]:

$$\begin{cases} U_1 = (Ni)[(\Delta/\Lambda)(1/c_3^c + 1/c_2^d) + (\gamma_{AM} + \gamma_{CM})] \\ U_2 = (Ni)[(\Delta/\Lambda)(1/c_2^c + 1/c_3^d) + (\gamma_{AM} + \gamma_{CM})] \end{cases} \quad (18)$$

where i is the current density, the unit is A/m^2; Δ is the thickness of a unit cell, the unit is m; Λ is the equivalent conductivity, the unit is S/m; γ_{AM}, γ_{CM} are the area resistance of the anion and cation exchange membrane, the units are $\Omega \cdot$m^2 and it can be neglected [26]; c_3^c is the solute concentration at the exit of concentrated cells of Regenerator 1, the unit is %; c_2^d is the solute concentration at the exit of diluted cells of Regenerator 1, the unit is%; c_3^d is the solute concentration at the exit of diluted cells of Regenerator 2, the unit is %. By analyzing Eqs. (7)–(10),

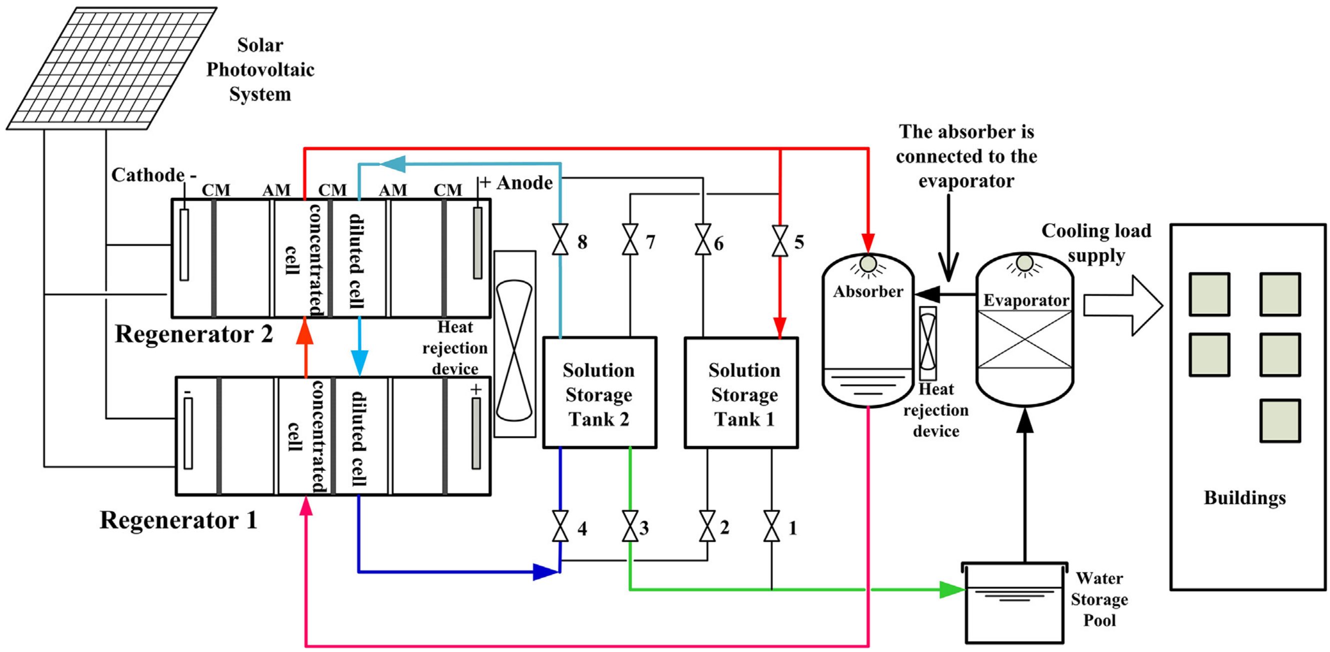


Fig. 6. Double-stage membrane regeneration system.

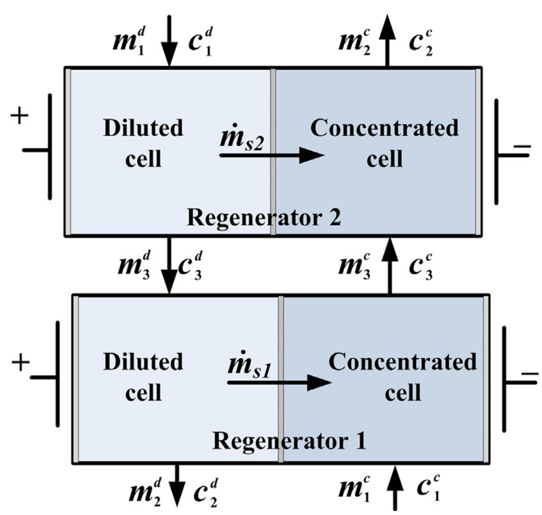


Fig. 7. Mass relationship of double-stage system.

some parameters are further explored:

$$c_2^c = \frac{m_1^c c_1^c + \dot{m}_s}{m_2^c} = \frac{m_1^c c_1^c + \dot{m}_s}{m_1^c + \dot{m}_s} \tag{19}$$

$$c_2^d = \frac{m_1^d c_1^d - \dot{m}_s}{m_1^d - \dot{m}_s} \tag{20}$$

$$c_3^c = \frac{m_1^c c_1^c + \dot{m}_{s1}}{m_1^c + \dot{m}_{s1}} \tag{21}$$

$$c_3^d = \frac{m_1^d c_1^d - \dot{m}_{s2}}{m_1^d - \dot{m}_{s2}} \tag{22}$$

Assume $m_1^d = k_2 m_1^c$, $\dot{m}_s = k_3 m_1^c$, U_2/U_1 is obtained:

$$U_2/U_1 = \frac{\frac{1+k_3}{c_1^c+k_3} + \frac{k_2-(1-k_1)k_3}{k_2c_1^d-(1-k_1)k_3}}{\frac{1+k_1k_3}{c_1^c+k_1k_3} + \frac{k_2-k_3}{k_2c_1^d-k_3}} \tag{23}$$

The analysis above shows the double-stage system not only has the potential to promote the current efficiency, but also changes the system's influential parameters. Compared Eq. (2) with Eq. (17), there are more factors related to the performance of double-stage system, and those factors are also complex, such as U_2/U_1. Therefore, optimizing those parameters is likely to improve the performance of the system. The next part will show the detail results we obtained.

3. Results and discussion

3.1. Experimental results and analysis

With Eq. (3), current efficiency can be calculated by concentration change between before and after regeneration. Meanwhile, concentration difference between concentrated cells and diluted cells can be measured. Use the logarithmic mean difference of (ρc) to define the concentration difference between the concentrated and diluted cells:

$$\Delta c_{cd} = \frac{(\rho_{i,c}c_{i,c} - \rho_{i,d}c_{i,d}) - (\rho_{o,c}c_{o,c} - \rho_{o,d}c_{o,d})}{\ln\frac{(\rho_{i,c}c_{i,c} - \rho_{i,d}c_{i,d})}{(\rho_{o,c}c_{o,c} - \rho_{o,d}c_{o,d})}} \tag{24}$$

$\rho_{i,c}$, $\rho_{i,d}$ are respectively the density of the solution entering the concentrated and diluted cells, kg/m^3; $c_{i,c}$, $c_{i,d}$ are respectively the mass concentration at the entrance of the concentrated and diluted cells, %; $\rho_{o,c}$, $\rho_{o,d}$ are respectively the density of the solution leaving the concentrated and diluted cells, kg/m^3; $c_{o,c}$, $c_{o,d}$ are respectively the mass concentration at the exit of the concentrated and diluted cells, %.

The initial LiCl concentration was 25% and the flow rates were 50 L/h for the solution entering the concentrated and diluted cells. The current intensity is 5 A. Fig. 8 shows the experimental results. The current efficiency decreases rapidly with the increasing concentration difference. It falls from 60% to 40% when the concentration difference rises from 0.14% to 1.4%. This is because with higher concentration difference, more reverse mass transfer happens according to the concentration gradient. It reduces the regeneration product and leads to low current efficiency. The practical *COP* is also calculated with the actual current efficiency and presented in Fig. 8. It drops from 2.9 to 2.1, corresponding to the rising concentration difference. The results are in accordance with the assumption made before and show the higher concentration difference between adjacent cells is very harmful to the performance. Therefore, it is believable the double-stage and

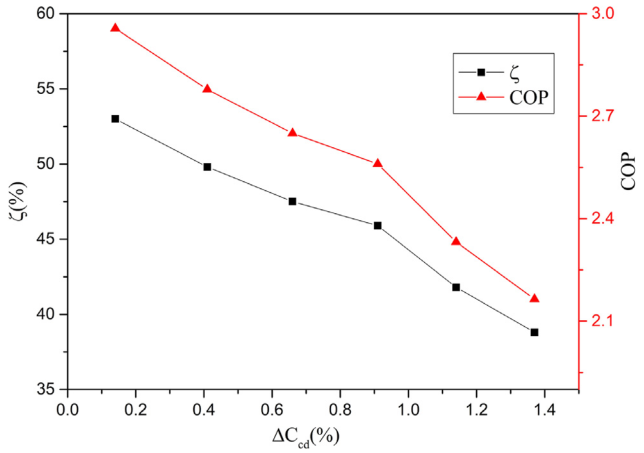


Fig. 8. Current utilization efficiency and *COP* with concentration differences.

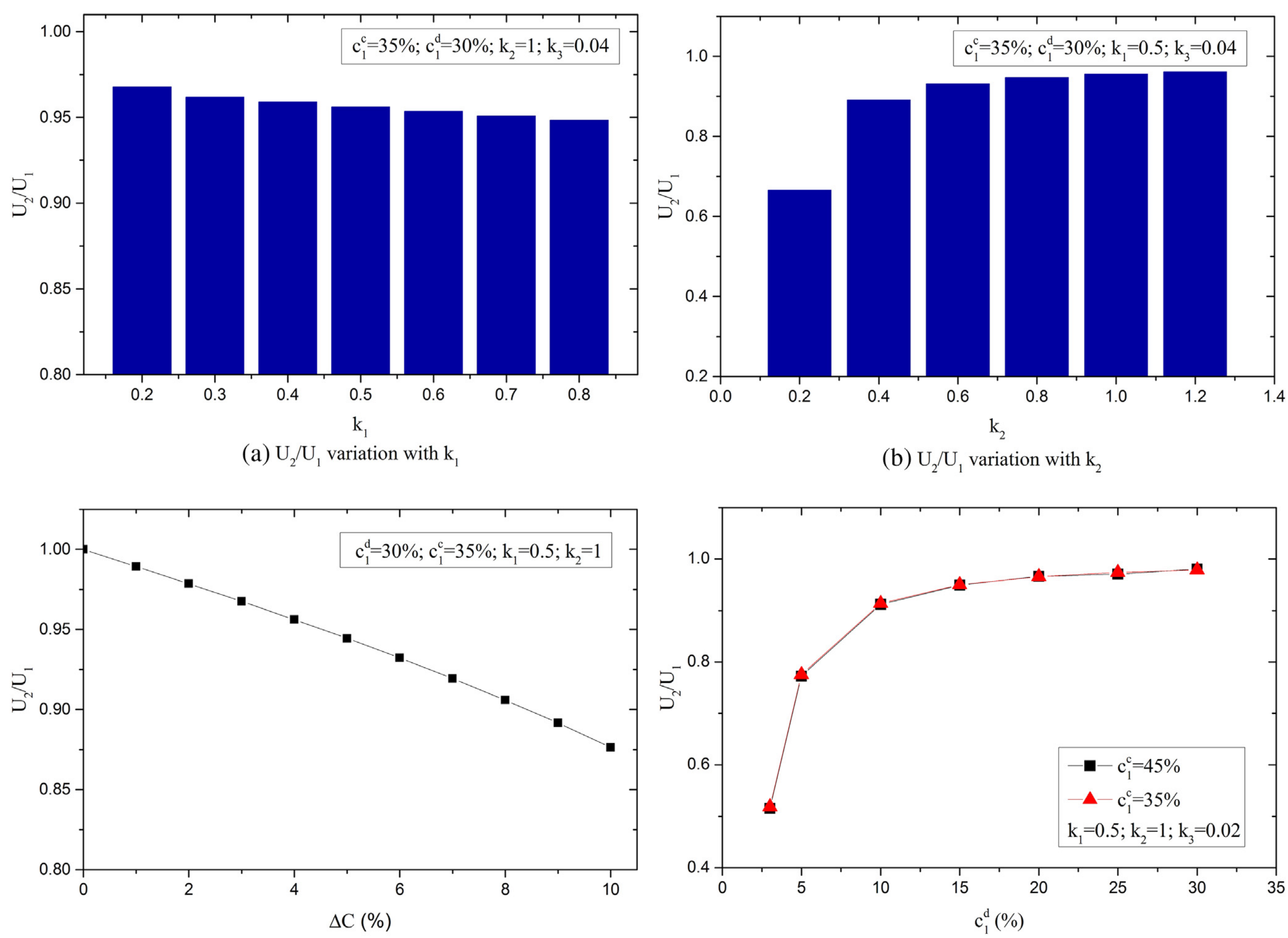
multi-stage system could improve the efficiency and make the system more stable by lowing the concentration difference in the regeneration process.

3.2. Performance analysis of the double-stage system

The *COP* of the double-stage system in Eq. (17), different from single-stage system, is extra influenced by the ratio of voltages applied on regenerators (U_2/U_1) and the solute mass transferred ratio (k_1). For other parameters, there are no essential differences between those of single-stage system, and they have been researched in related article [25]. Therefore, the following analysis is mainly aimed at these two parameters.

In order to accurately reveal the performance of the system, first, the range of U_2/U_1 should be known. From Eq. (23), it finds U_2/U_1 is decided by five parameters (k_1, k_2, k_3, c_1^c, c_1^d). Shown in Fig. 7, k1 stands for the mass transferred proportion in Regenerator 1; k_2 stands for the mass flow rate ratio of the solution entering the diluted cells of Regenerator 2 to the solution entering the concentrated cells of Regenerator 1; k_3 stands for the ratio of total mass transferred to the mass flow rate of the solution entering the concentrated cells of Regenerator 1, it approximates the concentration change of the solution in the concentrated cells after regeneration (defined as $\Delta c = c_2^c - c_1^c$). The variation of U_2/U_1 with different parameters is presented in Fig. 9(a)–(d).

Fig. 9(a) shows the value of U_2/U_1 slightly decreases with k_1 increasing when the other parameters are fixed. As k_1 increases, it means more regeneration product in Regenerator 1, so it demands higher applied voltage U_1, and thus U_2/U_1 decreases. Fig. 9 (b) shows the value of U_2/U_1 increases with higher k_2 when the other parameters are fixed. It reveals the influence of the flow rate ratio between the solution entering the diluted cells and the concentrated cells. Fig. 9(c) shows the value of U_2/U_1 decreases with higher concentration difference before and after regeneration when the other parameters are fixed. But the influence is small as the value of U_2/U_1 does not change too much.



(a) U_2/U_1 variation with k_1

(b) U_2/U_1 variation with k_2

(c) U_2/U_1 variation with ΔC

(d) U_2/U_1 variation with c_1^d

Fig. 9. U_2/U_1 variation with some parameters.

Fig. 9(d) indicates U_2/U_1 decreases rapidly when c_1^d is under 5% with the other parameters fixed, but it would not last for a long time. Also, Fig. 9(d) shows the value of U_2/U_1 is almost not influenced by the concentration of the solution entering the concentrated cells of Regenerator 1. In general, it can be found all the values of U_2/U_1 are larger than 0.8. Though it is possible that the ratio could be smaller with smaller k_2 in Fig. 9 (b), but k_2 would be set around 1 considering the practical application [20,25–27]. Therefore, a value of U_2/U_1 in the range of 0.8–1 could be reliable.

The *COP* of the double-stage system can be predicted by applying Eq. (17) with different k_1, U_2/U_1 and typical working concentration c_2^c [30,32]. Suppose LiCl solution is the adopted absorbent solution. Other parameters are listed in Table 1. The results are presented in Fig. 10(a), (b). Shown in Fig. 10(a), the *COP* increases with c_2^c decrease, which implies when the solute concentration after regeneration is adopted with a lower concentration, the performance of double-stage system could be very competitive. If c_2^c is 36%, for example, which means the mass concentration of the solute LiCl is 36%, the *COP* comes to 6 at least. Besides, Fig. 10(a) also indicates the *COP* floats between the curves, this is because U_2/U_1 is not stable when the system is working, and smaller U_2/U_1 can make the system achieve better performance. In Fig. 9(d), U_2/U_1 decreases with time going (c_1^d decrease with time going), which means the *COP* may be rising when the system keeps on working. Fig. 10 (b) shows smaller k_1 leads to a higher *COP*. Less solute mass transferred in Regenerator 1 helps the system more efficient, but the change is slight. Clearly, c_2^c has stronger impact on the *COP*.

It should be noted that, air-conditioning system has their *COP* strongly dependent from the supply cooling temperature and the heat rejection temperature, membrane regeneration system is no exception. The low evaporator temperature causes the decrease of refrigerating capacity per unit refrigerant, which means more refrigerant is needed, accompanied with the concentration difference between before and after regeneration getting larger, as discussed above, the *COP* will decrease. Similarly, the temperature of cooling water also changes the concentration difference, the higher temperature of cooling water, the lower the *COP*. Therefore, the determination of the concentration of absorbent solution should also consider the influence of temperatures.

Shown in Fig. 8, if the concentration difference reached to 2%, the current efficiency would be about 35%, which is far below the theoretical value 90%. It is practical to predict the actual *COP* of the double-stage system based on this actual efficiency. The values of *COP* are respectively evaluated with three common used absorbent solutions: LiCl, $CaCl_2$, and LiBr. The average voltage ratio is 0.9. The results are shown in Fig. 11. It can be found, within their typical working concentration ranges, the maximum *COP* is obtained from LiBr solution, which comes to 3. As a contrast, the maximum *COP* of LiCl and $CaCl_2$ are 2.5 and 2.8, respectively. That indicates LiBr will be a more favorable selection. But, taking into consideration of the practical application, the choice may be different as LiBr is very expensive while the gaps of performance between them are not too big.

The models for the double-stage system derivates from the single-stage system model which has been validated in the previous works [26,27]. Based on the experimental data, the results of the analysis are trustful for practical application. They can also be taken as a guide for designing the double-stage system for further research.

3.3. COP comparison between the double-stage system and single-stage system

The comparison has been made under the same total solute mass transferred, and the parameters of the solution are all the same. Assume cell pairs and applied voltage of single-stage system are twice than that of one regenerator of double-stage system, and the structures of the two regenerators are the same. Assume $\Delta COP = COP_{double} - COP_{single}$, and:

$$\frac{\Delta COP}{COP_{single}} = \frac{1}{U_2/U_1(1-k_1) + k_1} - 1 \tag{25}$$

Shown in Eq. (25), the results is influenced by $k1$ and U_2/U_1. Double-stage system is more energy efficient with a larger value of $\Delta COP/COP_{single}$. The results are presented in Fig. 12.

Fig. 12 implies double-stage system is more efficient as all $\Delta COP/COP_{single}$ are positive, and a smaller U_2/U_1 makes it more evident. When U_2/U_1 is 0.8, the *COP* of double-stage system is even about 15% higher than that of single-stage system. The results do not consider the current efficiency, so the performance of the double-stage could be better than the simulated results. It is because the actual current efficiency is better with smaller concentration difference between the concentrated and diluted cells, which is right the feature of the double-stage system. The results also indicate a smaller k_1 helps double-stage system with a larger *COP*, which tell us smaller solute mass transferred in Regenerator 1 is favorable to the performance.

3.4. Analysis of multistage system

More stages reduce the harmful concentration difference in mass transfer and improve the performance. Is the number of stages the more the better? Multi-stage system has more regenerators, so the concentration difference is lower than that of the double-stage system. It makes the system more efficient in theory. Similar to the double-stage system, the *COP* of the multi-stage system can be given as:

$$COPn = \frac{l_w M_s N \zeta (1 - c_{n,o,c})}{zFc_{n,o,c} U_1 \sum_{i=1}^{n} \frac{U_i}{U_1} k_i} \tag{26}$$

$c_{n,o,c}$ is the solute concentration at the exit of concentrated cells of Regenerator n,%; U_i is the voltage applied on Regenerator i, V; k_i is the mass transferred ratio between Regenerator i and 1.

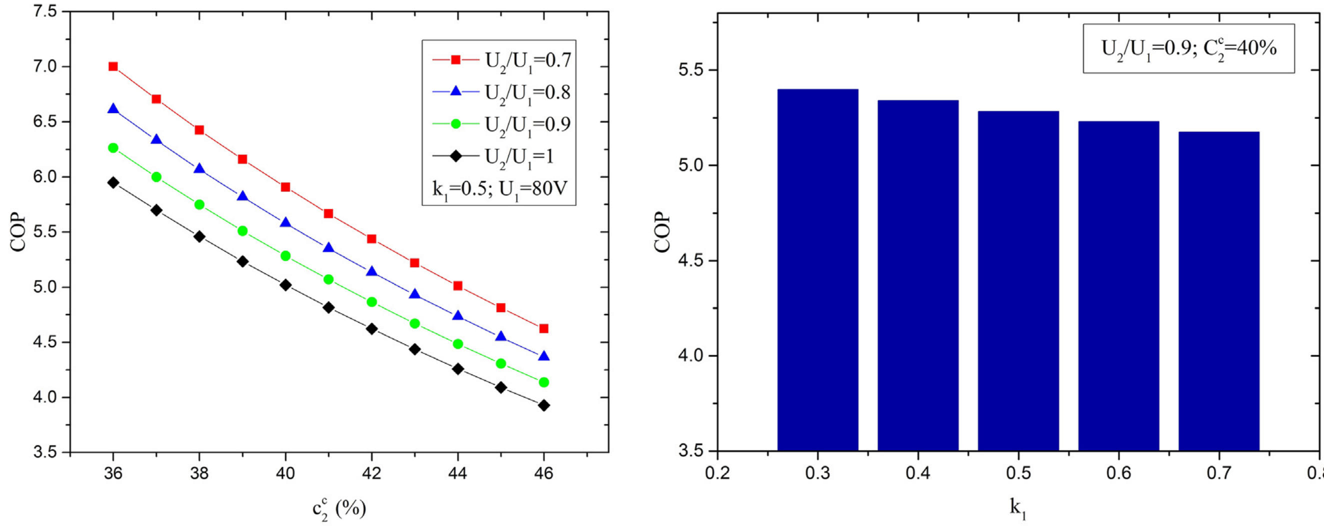
Though Eq. (26) would be too complicated to explore (Fig. 13) as there may be too many regenerators, it can be predicted that the *COP* of the multi-stage system decreases with the increase of solute concentration after regeneration. More regenerators help the voltage ratio smaller, which would make the system more efficient. We have chosen some typical values to predict the *COP* of multi-stage system, and the results are shown as Fig. 14. As expected, the *COP* gradually increases with the stages increase, which shows the potential of multi-stage system at performance improving, despite the slight rise of *COP*. Nevertheless, the benefits is limited with regenerator continually increasing, as excessive regenerators would cause the pipe connection complicated and the cost rises with more regenerators.

4. Conclusions

Membrane regeneration is a potential method used for absorption air-conditioning system, but the big concentration difference between the adjacent cells caused harmful reverse mass transfer. This phenomenon leads to lower current efficiency in the experiment. The double-

Table 1
Parameters for *COP* evaluation.

Parameter	Value	Specification
N	300	This value is from a typical ED product [12–14]
F	96485.3415 s·A/mol	
z	1	The absorbent is LiCl solution
ζ	90%	This value is from a typical ED product [12–14]
U_1	80 V	This value is from a typical ED product [12–14]
l_w	2484 kJ/kg	The evaporation temperature is 7 °C, the evaporation pressure is about 1 kPa



(a) COP variation with c_2^c and U_2/U_1 (b) COP variation with k_1

Fig. 10. *COP* variation with some parameters.

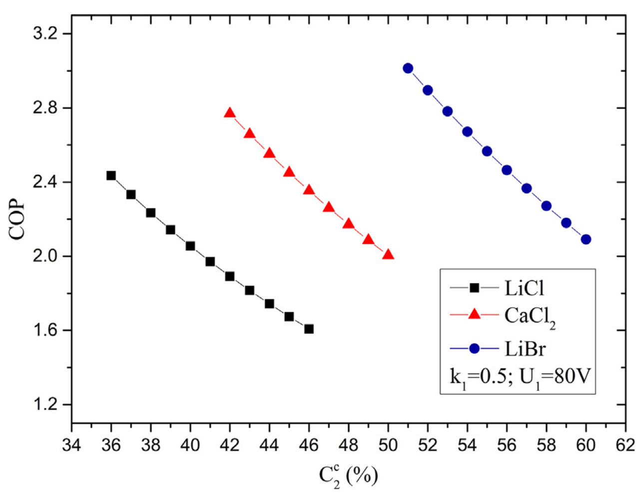


Fig. 11. Actual *COP* of double-stage system.

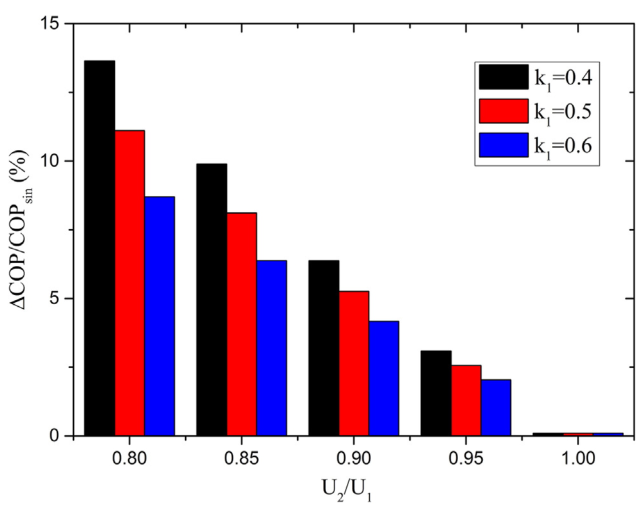


Fig. 12. *COP* comparison between double-stage system and single-stage system.

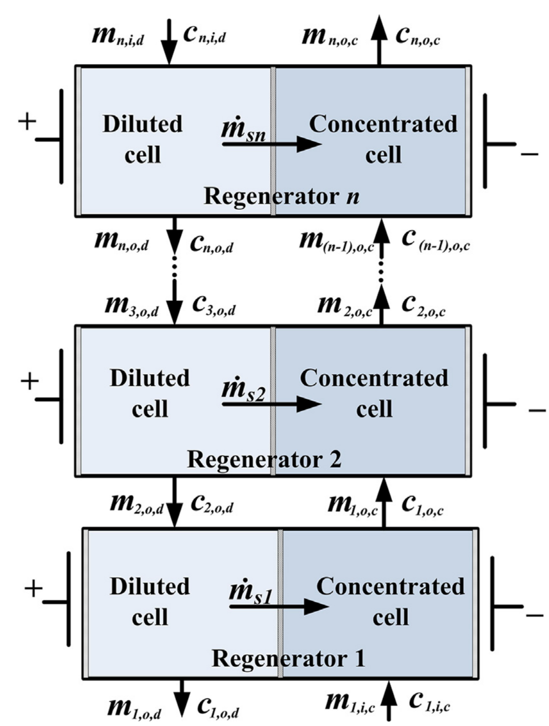


Fig. 13. Mass relationship of multi-stage system.

stage or multi-stage system could be a solution, as more stages reduce this concentration difference.

The model evaluating the whole performance of the double-stage membrane system has been established. The results have revealed the influence of some important parameters, like the voltage ratio U_2/U_1, the solute concentration c_2^c and the solute mass transferred ratio k_1. Among them, U_2/U_1 is stable within the range of 0.8–1. Smaller k_1 improves the performance. It also found smaller U_2/U_1, k_1 and c_2^c benefit the performance, and the solute concentration should be comprehensively considered the influence of temperature. Based on experimental data and actual current efficiency, the actual *COP* of the double-stage system can approach 3, which is competitive. Compared with single-stage system, double-stage system has a more than 15% improvement on performance.

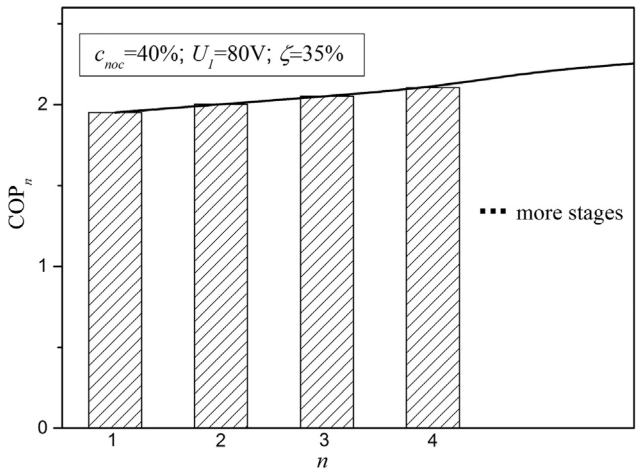


Fig. 14. *COP* of multi-stage system.

Voltage ratio of multi-stage system is smaller compared with single/double-stage system. It would be more efficient, but excessive regenerators may be not good as the pipe connection is more complicated and the cost is higher. Besides, the benefit is limited with the increasing number of regenerators. Therefore, it is important to find a method to reduce the harmful concentration difference without adding too many stages. It needs more theoretical and experimental work in the future.

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